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Undergraduate Thesis

Title: Computer Predesign of Cooke Triplet Anastigmat

Submitted by: Frank Vanek

On: 16 May, 1975

To: ROCHESTER INSTITUTE OF TECHNOLOGY

Department of Photographic Science and Instrumentation

Thesis Advisor: John Carson

6923917

Abstract:

There are many methods for designing the Cooke Triplet Anastigmat. In this thesis, one of them is programmed into a computer in BASIC language. Because of the length of the program, it had to be split into two separate programs using a data file to save data produced by the first and needed by the second.

The first program uses the equation for system power, and the equations for Petzval curvature, longitudinal and lateral chromatic aberrations, space ratio to solve for the powers and spacings of the elements. Solution is accomplished by the Crout method of simultaneous equation solution and by iteration.

The second program solves for the bendings of the elements. Assuming a value for the first curvature, it solves for the second and third using the equations for coma and astigmatism, respectivly. The value of spherical aberration is used to check the result, and if not correct a new value is calculated for the first cuvature.

The program was checked by carrying through an example that was also solved by hand, and comparing the results. The program has successfully solved two examples.

Introduction:

Everyone in the photographic field knows that computers are used to design lenses. Those in optics know computers have been in use for about thirty years. Even so, the problem of programming computers to design lenses is not a trivial one. Optical programming is still an area of extensive research for both government and industry.

Most optical programming works to optimize a design that has already been completed in rough form; the computer makes small adjustments to refine the performance of the test lens. Very often the final performance of the new design depends on the quality of the rough design. A well-known lens is the Cooke Triplet Anastigmat, which consists of a negative element between two widely spaced positive elements. This lens is unique; it has just enough degrees of freedom to allow the designer to control the power, lateral and longitudinal chromatic aberrations, and the Seidel aberrations. Algorithms for the solution of the design have been published prior to and since the turn of the century; the lens was invented in 1893 by H. Dennis Taylor.

?

While there are almost as many methods of using these equations as there are designers, any design formulated by the methods is excellent for subsequent treatment in an optimization program. Thousands of these lenses are in use today in moderately priced cameras.

calculations

The~~se methods~~ are usually done with pencil and desk calculator, and sometimes with some aid from a computer. No one has published a computer program for this purpose. This is the substance of the thesis: to program the computer in BASIC language for predesign of the Cooke Triplet Anastigmat. The method used is basically the one proposed by Schwarzschild about 1904, taken from Dr. Kingslake's notes.

A predesign deals only with first order optics and thin elements; the equations are completely true only for rays differentially close to the axis, and elements so thin as to be considered of zero thickness. This approximation to rays at finite height and elements of finite thickness is good enough that the first order predesign can be converted into a rough design by assignment of thicknesses to the elements. The design would then be computer optimized.

Background Theory and Plan of Attack:

The eight aberrations include lateral and longitudinal chromatic aberration, Petzval curvature, distortion, astigmatism, spherical aberration and coma. System power (inverse focal length) is not actually an aberration, but the equation is in the same form as aberration equations and is used in the same way. For the sake of brevity, system power will be referred to as an aberration.

The lens has three elements, and thus three powers, one for each element; two spacings between the elements and three bendings, one for each element; for a total of eight degrees of freedom.

To greatly simplify calculations, the aperture stop is assumed to be located at the second element: in other words, at zero distance from it.

The basic method used is to choose an aim value for each of the aberrations, then solve a convenient combination of them for some of the unknown variables. These aim or residual values would not be equal to zero; by using non-zero values it is possible to compensate for higher order aberrations that will appear when thicknesses are added to the elements. The only way of estimating these residuals is through experience with this lens, or by trial and error, following the design to completion each time. They would also depend on the purpose of the lens; in a fast lens, for example, spherical aberration would have to be very carefully controlled.

Procedure: Part One

The first task is to determine the powers and spacings. Four aberrations are functions of element power: system power, longitudinal chromatic, Petzval curvature and lateral chromatic. To solve for five items, a fifth relation is needed, but there is no aberration to supply it. Therefore, one is defined; the ratio of the spacings must be some constant K; which is set to an arbitrary value at first. When the design is completed, K can be changed to reduce distortion.

The first step is to set up a panel of simultaneous equations:

$$y_a\phi_a + y_b\phi_b + y_c\phi_c = y_a\Phi$$

$$(y_a/V_a)\phi_a + (y_b/V_b)\phi_b + (y_c/V_c)\phi_c = -L'ch*u_o'^2$$

$$(1/N_a)\phi_a + (1/N_b)\phi_b + (1/N_c)\phi_c = Ptz$$

Where: y=ray height for the marginal ray (first order)

ϕ=power (reciprocal focal length) of each element

V=V number of the glass of each element

N=index of refraction of each glass N_D

L'ch=longitudinal axial chromatic aberration contribution

Ptz=Petzval curvature of the system

u_o'=entering angle of the marginal ray from axial object point

Φ=total system power

If the object is taken at infinity, then u_o' equals zero, and y_a can be calculated as one half of the focal length divided by the aperture. Then ϕ_a, ϕ_b, ϕ_c and y_b, y_c are unknowns. Since the first element is converging, $y_b < y_a$ and $y_c > y_b$. We can then choose "likely" values for y_b and y_c, leaving the path clear for solution of ϕ_a, ϕ_b, ϕ_c. The Crout method was used to perform the simultaneous equation solution.

Once the powers are known, the spacings may be calculated, then K and T'ch, the space ratio and lateral chromatic. Unless we have been extremely lucky in our choice of y_b and y_c, these will not be at their aim values. A better approximation can be calculated using a method used in electronic engineering: the Newton-Raphson method. This method uses two simultaneous equations in this case:

$$\Delta K = \frac{\partial K}{\partial y_b} \Delta y_b + \frac{\partial K}{\partial y_c} \Delta y_c$$

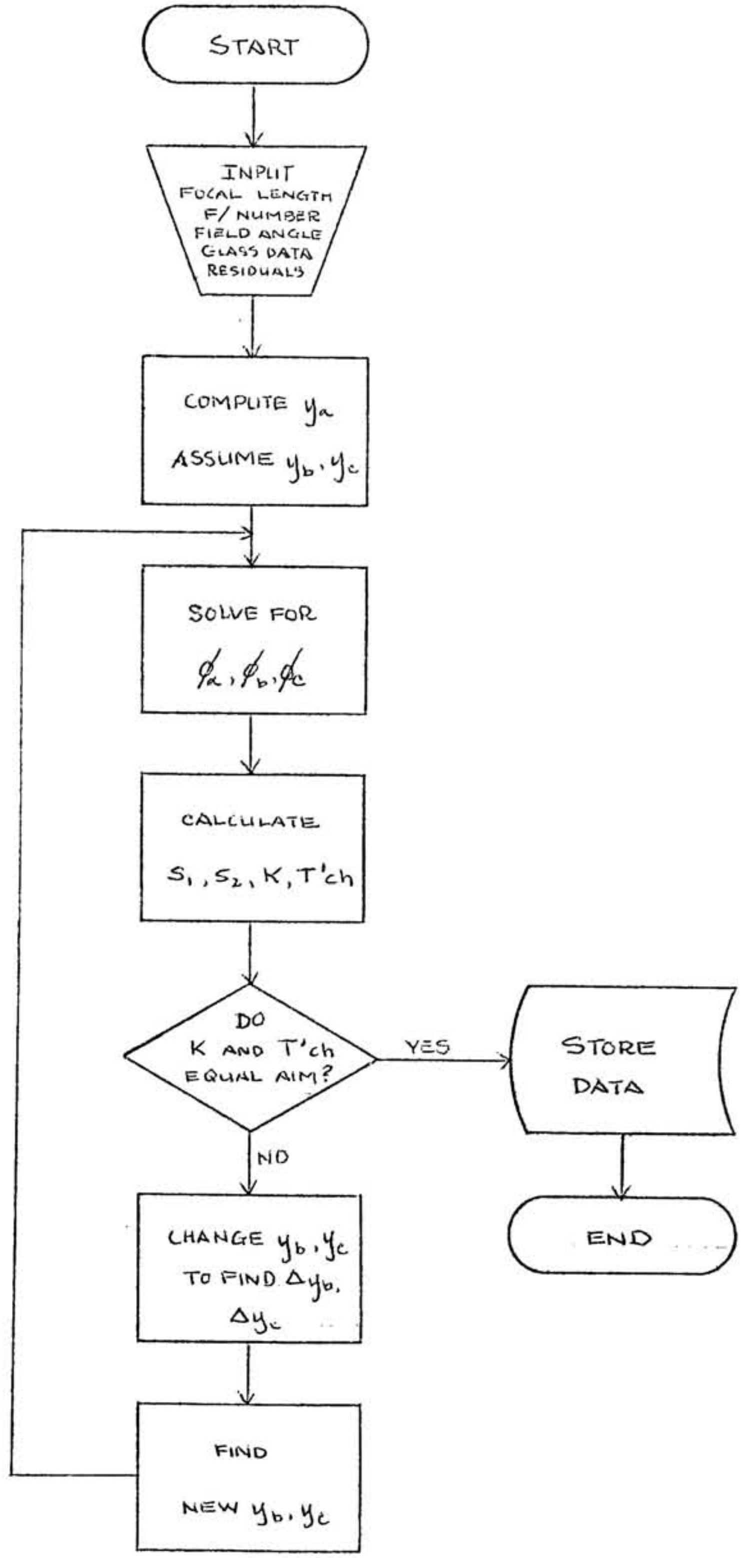
$$\Delta T'ch = \frac{\partial T'ch}{\partial y_b} \Delta y_b + \frac{\partial T'ch}{\partial y_c} \Delta y_c$$

By varying y_b only, it is possible to determine $\frac{\partial K}{\partial y_b}$ and $\frac{\partial T'ch}{y_b}$. The same technique is used to find $\frac{\partial K}{\partial y_c}$ and $\frac{\partial T'ch}{y_c}$. The equations can then be solved for the change in y_b and y_c needed to achieve the aim K and T'ch. To prevent the computer from overshooting the change is limited to 0.001 times the y value it is applied to. This does not affect accuracy, but speeds convergence. Since the functions are not straight lines, convergence would not be immediate. The new y_b and y_c would be substituted for the arbitrary values, and the powers solved again. The whole process would be repeated as many times necessary until K and T'ch converge on the aim values. Here is a test example, where the aim values for K and T'ch are 1 and 0 respectively ("E-04" means "times 10^{-4}").

Y(2)	K	Y(3)	T'CH
.838889	2.41458	1.00000	-1.13694E-02
.866339	1.45233	.954036	-2.13682E-03
.863186	1.22131	.954990	-7.60330E-04
.861771	1.12788	.955945	-2.52056E-04
.861411	1.09416	.956901	-1.21136E-04
.861342	1.07541	.957858	-8.37574E-05
.861323	1.05923	.958816	-6.24511E-05
.861313	1.04354	.959775	-4.43484E-05
.861306	1.02806	.960735	-2.77336E-05
.861301	1.01276	.961695	-1.23338E-05
.861299	1.00003	.962503	-1.81969E-07
.861298	1.00000	.962502	-9.64475E-12

With this process completed the powers and spacings are known. The program had by this point almost filled the memory core available. Instead of proceeding to Part Two, pertinent data is stored under the reference name of the lens in a data file. Some of the data used in Part Two is calculated at this point and stored so that more data from Part One can be discarded, reducing net storage space needed.

Chart 1 is a simplified flow chart of the first program.


START
INPUT
FOCAL LENGTH
F/NUMBER
FIELD ANGLE
GLASS DATA
RESIDUALS
COMPUTE y_a
ASSUME y_b, y_c
SOLVE FOR
ϕ_a, ϕ_b, ϕ_c
CALCULATE
S_1, S_2, K, T'ch
DO
K AND T'ch
EQUAL AIM?
YES
STORE
DATA
END
NO
CHANGE y_b, y_c
TO FIND Δy_b,
Δy_c
FIND
NEW y_b, y_c

The first task of the second program is to retrieve the data stored from the first. This is done automatically once the operator inputs the reference name.

The total curvature of each element is a function of element power and index of refraction. This specifies the <u>relationship</u> of the front surface to the rear surface curvature only. There are still an infinite number of front or rear curvatures that satisfy that power and index, but each of these possible bendings has different aberration contributions. For example, the first element could be made into a meniscus element, strongly bent; or a double convex element, weakly bent; both with the same power. Their spherical, coma, and astigmatism contributions would be different. The purpose of the second program is to "bend" the three elements until the sum of their individual aberration contributions equals the aim residual values.

To make this task easier, the aberration equations are placed in quadratic coefficient form. For example, the equation for the spherical contribution is:

$$SC^* = \frac{-y^4}{u_k'^2}\left(G_1 c^3 - G_2 c^2 c_1 + G_3 c^2 v + G_4 c c_1^2 - G_5 c c_1 v + G_6 c v^2\right)$$

Where: G_1 through G_6 are the G-sums dependent on index of refraction

c=total curvature for element in question

u_k'=final angle for the marginal ray = u_o'

v=the front curvature for that element

It can be noted that there are terms in c_1^2, terms in c_1, and constant terms. These can be collected and the equation placed in the form: $SC^* = a_0 + a_1 c_1 + a_2 c_1^2$

Where: $a_0 = \frac{-y^4}{u_k'^2}(G_1c^3 + G_3c^2v + G_6cv^2)$

$$a_1 = \frac{y^4}{u_k'^2}(G_2c^2 + G_5cv)$$

$$a_2 = \frac{-y^4G_4c}{u_k'^2}$$

A summary of the equations is in Appendix 4.

These coefficient expressions are of a convenient size for programming. Once calculated, they can be used to find the aberration value if c_1 is known, or solve for c_1 if the aberration contribution is known.

After the data is removed from storage, constants used through the program are calculated. These include the G-sums, total curvatures, v's, and also the astigmatism contribution for element B: AC_b. Since the stop is located at element B, the astigmatism there is independent of bending, and the coma expression is linear rather than quadratic.

To start the process, an arbitrary value for the first curve of the first element, c_{1a}, is assumed. If set equal to total curvature, the element is plano-convex, a reasonable starting point. It is then possible to compute SC_a^*, CC_a^*, and AC_a^*: spherical, coma, and astigmatism contributions for element A. The star superscript indicates that the contribution is at an element not located at the aperture stop.

Since total aim astigmatism, $Ast\dot{s}$, is known, AC_b is constant and AC_a^* has been calculated, AC_c^* is known, since $AC_a^*+AC_b+AC_c^*=Ast\dot{s}$. The astigmatism equation for element C is placed in the form $AC_c^* = d_6+ d_7c_{1c}+ d_8c_{1c}^2$, so the well known quadratic formula may be used to solve for the two values of c_{1c} that are roots of the equation. Usually the smaller in magnitude of these is used, since strongly bent elements are generally not desirable. It is then possible to calculate CC_c^* and SC_c^*.

The same method is used to solve for c_{1b}, using coma as the unknown, since $CC_b = \text{Coma}'s - CC_a^* - CC_c^*$. Since the stop is at B, the coma equation can be placed in the form $CC_b = b_3 + b_4 c_{1b}$, so only one root of the equation is necessary. SC_b is calculated, then $LA' = SC_a^* + SC_b + SC_c^*$.

Since the value of c_{1a} was assumed, LA' is not likely to be the aim value. Since LA' is close to being a quadratic function of c_{1a}, a good approximation of a new c_{1a} can be reached by choosing two more values of c_{1a}, finding new values for LA' by repeating the process outline above. These can be arranged into a panel of simultaneous equations:

$$LA_1' = A c_{1a1}^2 + B c_{1a1} + C$$

$$LA_2' = A c_{1a2}^2 + B c_{1a2} + C$$

$$LA_3' = A c_{1a3}^2 + B c_{1a3} + C$$

The Crout method is then used to solve for the coefficients A, B, and C. Since the aim LA' is known, the quadratic formula may be used again to find the two values of c_{1a} for the next trial. Usually the smaller of these is picked to avoid strong bending. The entire process is repeated, starting with the calculation of SC_a^*, CC_a^*, and AC_a^*. Since this new c_{1a} is only an approximation of the true value, the process would have to be repeated a number of times until LA' equals the aim value.

In the case of both c_{1a} and c_{1c} the operator must choose the smaller or larger root; the computer prints:

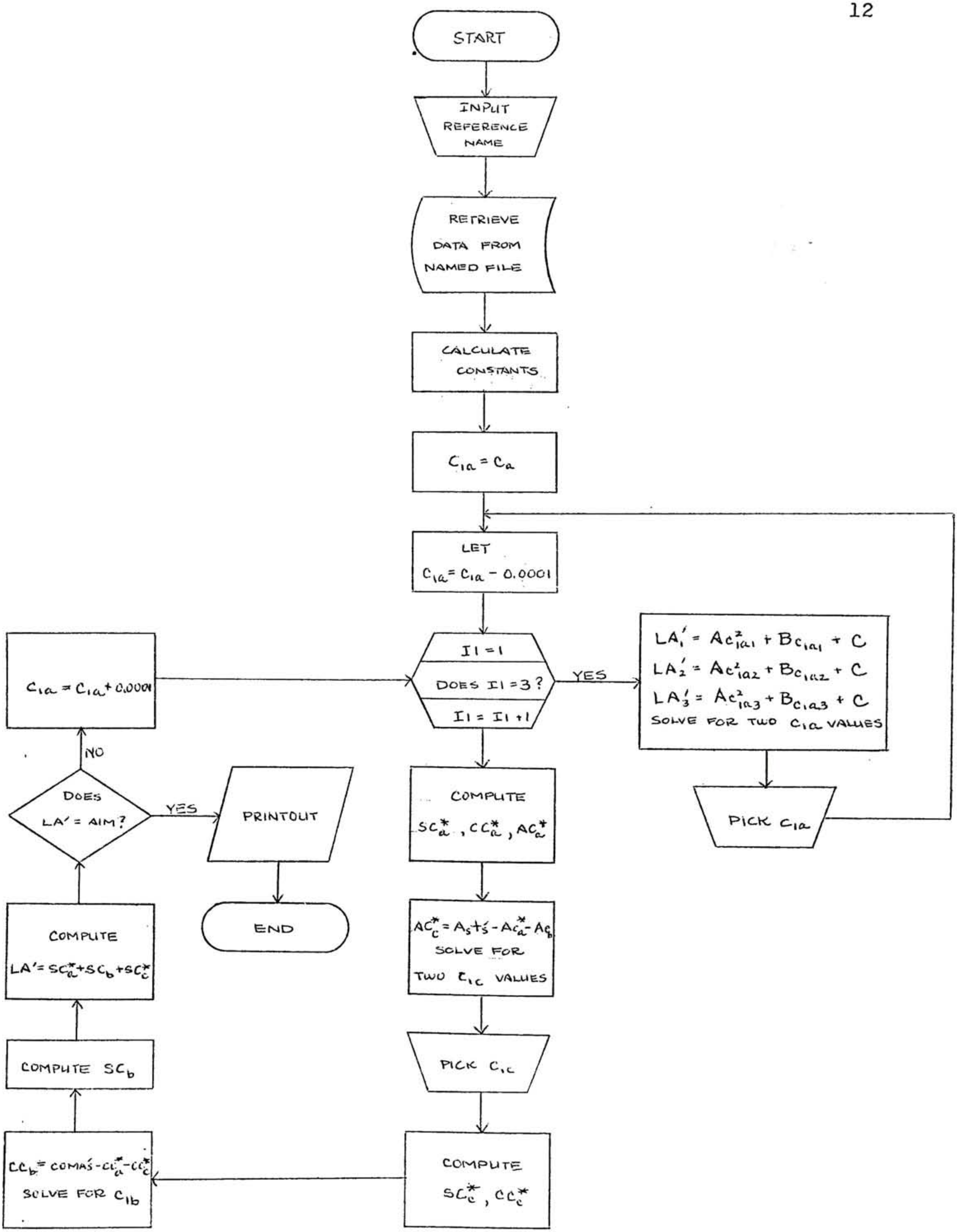
```
THE VALUES OF C(3,1) ARE:-.628841     2.64839E-02
PICK LARGE OR SMALL    ?S
C(1)            C(3)            LA'
 .237943          2.64839E-02  -5.27260E-02

THE FIRST CURVE FOR THE NEXT TRIAL CAN BE  .231370 OR  .296862
PICK LARGE OR SMALL    ?S
```

The first line indicates the two roots for c_{1c}. The next asks the operator to choose. If the operator had typed any character string starting with "L", the larger value would be used. Otherwise the smaller in magnitude is automatically used, as in this case. The computer then displays the values used in that run through, and the resulting LA'. It computes the two new roots for the first curve, and asks again for a choice. In this way the operator interacts continuously with the program.

For the purposes of the program c_{1a} is actually started at 0.0001 less than $c_{3,1}$, then incremented twice in a loop, adding 0.0001 each time. This produces the three c_{1a} and LA' values needed to fix the parabola at 0.0001 intervals of c_{1a}. This same technique is used for the new c_{1a} to provide three values again.

Chart 2 is a simplified flow chart of the second program.


START
INPUT REFERENCE NAME
RETRIEVE DATA FROM NAMED FILE
CALCULATE CONSTANTS
$C_{1a} = C_a$
LET $C_{1a} = C_{1a} - 0.0001$
$I1 = 1$
DOES $I1 = 3$?
$I1 = I1 + 1$
YES
$LA'_1 = Ac^2_{1a1} + Bc_{1a1} + C$
$LA'_2 = Ac^2_{1a2} + Bc_{1a2} + C$
$LA'_3 = Ac^2_{1a3} + Bc_{1a3} + C$
SOLVE FOR TWO C_{1a} VALUES
PICK C_{1a}
COMPUTE SC^*_a, CC^*_a, AC^*_a
$AC^*_c = A_s + t_s' - AC^*_a - AC_b$
SOLVE FOR TWO C_{1c} VALUES
PICK C_{1c}
COMPUTE SC^*_c, CC^*_c
$CC_b = COMAS' - CC^*_a - CC^*_c$
SOLVE FOR C_{1b}
COMPUTE SC_b
COMPUTE $LA' = SC^*_a + SC_b + SC^*_c$
DOES $LA' = AIM$?
NO
YES
$C_{1a} = C_{1a} + 0.0001$
PRINTOUT
END

Summary:

Here is a summary of which degrees of freedom control which aberrations:

Degrees of Freedom	Method	Item
Three Powers	Simultaneous Solution	System Power
Two Spacings		Longitudinal Chromatic
		Petzval Curvature
	Iteration	Lateral Chromatic
		Distortion
Three Bendings	Iteration	Spherical Aberration
		Coma
		Astigmatism

In this program distortion is not calculated or corrected. Thicknesses should be added before distortion is determined, and then K would be changed and the predesign repeated with the new K.

Program Check:

The checking and debugging process is threefold. First, the program must be run to see if it functions to completion. When it does not, and all obvious errors have been corrected, the next step is to start computing the test example by hand, comparing results to those generated by the computer until a significant difference is found and the erronious equation pinpointed. Once this first example is completed, and the program operational, a second example is run and the results checked against the hand calculated values.

The program was checked using the example in Dr. Kingslake's notes, and the complete example can be found in Appendix 3. The answers were not completely identical, but the differences small enough to be attributed to differences in rounding. They generally agreed to five decimal places.

The program was then checked by an example from Mr. Carson; the correct values for the output were known only to him. Again, the answers agreed to a reasonable number of places.

Therefore, the program works.

Use of Program in Design Process:

Since the predesign is an approximate design with zero thickness assumed for the elements, the next step in the design process is to add thicknesses. Since thick elements have a Gauss seperation, the spacings must be adjusted to compensate. The thicknesses added must be sufficient to allow for trimming, centering and mounting of the elements with the required clear apertures.

These calculations would produce a design which could actually be built, but tracing exact rays would reveal that is not yet good enough. The aberration values found would be used to correct the residuals used in the predesign, and the predesign would be repeated. If the original guess for the residuals was reasonably good, not too many repetitions of the process would be needed to minimize the aberrations in the rough design. The design could then be computer optimized, and built if the finished design meets specifications.

APPENDIX 1

Program

```
10 REM  CØMPUTER PREDESIGN ØF CØØKE TRIPLET ANASTIGMAT
20 REM INPUT, PØWER AND SPACING PRØGRAM
30 REM FRANK VANEK, 5/8/75
40 DIM A(3,4),G(3),N(3),P(3),S(2),T(3),U(3),V(3),Y(5)
50 FØR I1=1 TØ 10
60 PRINT
70 NEXT I1
80 PRINT "WHAT IS LENS DESIGNATIØN";
90 INPUT M1
100 PRINT "WHAT IS THE DESIRED FØCAL LENGTH";
110 INPUT F1
120 PRINT "WHAT IS THE DESIRED MAXIMUM APERTURE";
130 INPUT F2
140 PRINT "WHAT IS THE DESIRED MAXIMUM FIELD ANGLE (DEG)";
150 INPUT F3
160 FØR I1=1 TØ 3
170 PRINT "GLASS FØR ELEMENT"I1;
180 INPUT G(I1)
190 PRINT "N("I1")=";
200 INPUT N(I1)
210 PRINT "V("I1")=";
220 INPUT V(I1)
230 NEXT I1
240 Y(1)=F1/2/F2
250 U2=-TAN(RAD(F3))
260 N1=1
270 D3=1E-6
280 D4=1E-6
290 PRINT "WHAT IS THE AIM VALUE FØR:"
300 PRINT "PETZVAL CURVATURE ";
310 INPUT A1
320 PRINT "L'CH  ";
330 INPUT A2
340 PRINT "T'CH  ";
350 INPUT A3
360 PRINT "AST'S";
370 INPUT A5
380 PRINT "CØMA  ";
390 INPUT A6
400 PRINT "LA'   ";
410 INPUT A7
420 PRINT "K     ";
430 INPUT K1
440 U1=1/2/F2
450 U3=0
460 PRINT
470 PRINT
480 PRINT "Y(2)","K","Y(3)","T'CH"
490 Y(2)=Y(1)*.8
500 Y(3)=Y(1)*.9
>
```

```
510 IF Y(1)↑2/V(1)<>Y(3)↑2/V(3) THEN 530
520 Y(3)=Y(3)+.1
530 A(1,4)=U1-U3
540 REM CRØUT METHØD STARTS HERE
550 A(2,4)=-A2*U1↑2
560 A(3,4)=A1
570 FØR I1=1 TØ 3
580 A(1,I1)=Y(I1)
590 A(2,I1)=Y(I1)↑2/V(I1)
600 A(3,I1)=1/N(I1)
610 NEXT I1
620 A(1,2)=A(1,2)/A(1,1)
630 A(1,3)=A(1,3)/A(1,1)
640 A(1,4)=A(1,4)/A(1,1)
650 A(2,2)= A(2,2)-A(2,1)*A(1,2)
660 A(3,2)=A(3,2)-A(3,1)*A(1,2)
670 A(2,3)=(A(2,3)-A(2,1)*A(1,3))/A(2,2)
680 A(2,4)=(A(2,4)-A(2,1)*A(1,4))/A(2,2)
690 A(3,3)=A(3,3)-A(3,1)*A(1,3)-A(3,2)*A(2,3)
700 A(3,4)=(A(3,4)-A(3,1)*A(1,4)-A(3,2)*A(2,4))/A(3,3)
710 P(3)=A(3,4)
720 P(2)=A(2,4)-A(2,3)*P(3)
730 P(1)=A(1,4)-A(1,2)*P(2)-A(1,3)*P(3)
740 U4=U3+Y(1)*P(1)
750 U5=U4+Y(2)*P(2)
760 S(1)=(Y(1)-Y(2))/U4
770 S(2)=(Y(2)-Y(3))/U5
780 K2=S(2)/S(1)
790 Y(4)=S(1)*U2/(1-S(1)*P(1))
800 Y(5)=-K2*Y(4)
810 A4=-1/U1*(Y(1)*Y(4)*P(1)/V(1)+Y(3)*Y(5)*P(3)/V(3))
820 IF N1<>1 THEN 850
830 PRINT Y(2),K2,Y(3),A4
840 REM NEWTØN-RAPHSØN METHØD STARTS HERE
850 ØN N1 GØTØ 870,940,1020
860 REM NEXT TWØ LINES ARE EXIT
870 IF ABS(K1-K2)>1E-8 THEN 890
880 IF ABS(A3-A4)<1E-8 THEN 1230
890 Y(3)=Y(3)+D4
900 N1=2
910 T1=K2
920 T2=A4
930 GØTØ 530
940 D1=T1-K2
950 D2=T2-A4
960 S2=D1/D4
970 S4=D2/D4
980 N1=3
990 Y(2)=Y(2)+D3
1000 Y(3)=Y(3)-D4
1010 GØTØ 530
1020 S1=(T1-K2)/D3
1030 S3=(T2-A4)/D3
1040 Y(2)=Y(2)-D4
1050 D1=T1-K1
>
```

```
1060 D2=T2-A3
1070 D3=(S2*D2-S4*D1)/(S2*S3-S1*S4)
1080 IF S2=0 THEN 1110
1090 D4=(D1-S1*D3)/S2
1100 GØTØ 1120
1110 D4=(D2-S3*D3)/S4
1120 IF D3<>D5 THEN 1160
1130 IF D4=D6 THEN 1230
1140 REM NEXT 11 LINES LIMIT CHANGE IN Y'S AND RESET FØR
1150 REM NEXT RUN-THRØUGH
1160 IF D3<.001*Y(2) THEN 1180
1170 D3=.001*Y(2)*SGN(D3)
1180 Y(2)=Y(2)+D3
1190 D5=D3
1200 D3=1E-6
1210 IF D4<.001*Y(3) THEN 1230
1220 D4=.001*Y(3)*SGN(D4)
1230 Y(3)=Y(3)+D4
1240 D6=D4
1250 D4=1E-6
1260 N1=1
1270 GØTØ 530
1280 REM EXIT: ØUTPUT AND DATA STØRAGE START HERE
1290 PRINT
1300 PRINT
1310 PRINT "PØWERS",P(1),P(2),P(3)
1320 PRINT "SPACINGS","          "S(1)"        "S(2)
1330 H1=Y(5)-Y(3)*(U2+Y(4)*P(1)+Y(5)*P(3))/U1
1340 Q1=Y(4)/Y(1)
1350 V1=U3/Y(1)
1360 Q3=Y(5)/Y(3)
1370 V3=U5/Y(3)
1380 V2=U4/Y(2)
1390 ØPEN M1;"007",Ø
1400 PUT 1
1410 FØR I1=1 TØ 3
1420 U(I1)=Y(I1)
1430 NEXT I1
1440 PUT F1,F2,F3
1450 MAT PUT N
1460 MAT PUT V
1470 MAT PUT U
1480 PUT V1,V2,V3
1490 PUT Q1,Q3
1500 PUT U1,H1
1510 PUT A5,A6,A7
1520 MAT PUT P
1530 MAT PUT S
1540 MAT PUT G
1550 CLØSE Ø
1560 FØR I1=1 TØ 10
1570 PRINT
1580 NEXT I1
1590 END
>
```

```
10 REM CØMPUTER PREDESIGN ØF CØØKE TRIPLET ANASTIGMAT
20 REM BENDING PRØGRAM
30 REM FRANK VANEK, 5/4/75
40 DIM A(3,4),C(3,2),G(8,3),L(3),N(3),P(3),S(2),V(3),Y(3),Z(3)
50 FØR I1=1 TØ 10
60 PRINT
70 NEXT I1
80 PRINT "WHAT IS DESIGNATIØN ØF LENS";
90 INPUT M1
100 ØPEN M1;"007",1
110 GET N1
120 IF N1=1 THEN 150
130 PRINT "INCØRRECT DATA FILE ACCESS"
140 STØP
150 GET F1,F2,F3
160 MAT GET N
170 MAT GET V
180 MAT GET Y
190 GET V1,V2,V3
200 GET Q1,Q3
210 GET U1,H1
220 GET A5,A6,A7
230 MAT GET P
240 MAT GET S
250 MAT GET Z
260 CLØSE 1
270 FØR I1=1 TØ 3
280 T1=N(I1)
290 G(1,I1)=T1↑2*(T1-1)/2
300 G(2,I1)=(2*T1+1)*(T1-1)/2
310 G(3,I1)=(3*T1+1)*(T1-1)/2
320 G(4,I1)=(T1+2)*(T1-1)/2/T1
330 G(5,I1)=2*(T1+1)*(T1-1)/T1
340 G(6,I1)=(3*T1+2)*(T1-1)/2/T1
350 G(7,I1)=(2*T1+1)*(T1-1)/2/T1
360 G(8,I1)=T1*(T1-1)/2
370 NEXT I1
380 L1=P(1)/(N(1)-1)
390 L2=P(2)/(N(2)-1)
400 L3=P(3)/(N(3)-1)
410 G2=-H1↑2*P(2)/2
420 C(1,1)=L1
430 C(1,1)=C(1,1)-.0001
440 FØR I1=1 TØ 3
450 C(1,2)=C(1,1)-L1
460 REM CØEFFICIENTS FØR ELEMENT A
470 T1=-Y(1)↑4*(G(1,1)*L1↑3+G(3,1)*L1↑2*V1+G(6,1)*L1*V1↑2)/U1↑2
480 T2=Y(1)↑4*(G(2,1)*L1↑2+G(5,1)*L1*V1)/U1↑2
490 T3=-Y(1)↑4*G(4,1)*L1/U1↑2
500 T4=H1*Y(1)↑2*(G(7,1)*L1*V1+G(8,1)*L1↑2)+Q1*U1*T1
>
```

```
510 T5=-.25*H1*Y(1)↑2*G(5,1)*L1+T2*Q1*U1
520 T6=Q1*U1*T3
530 T7=Q1↑2*T1+2*Q1*H1*Y(1)↑2*(G(7,1)*L1*V1+G(8,1)*L1↑2)/U1
540 T7=T7-H1↑2*P(1)/2
550 T8=Q1↑2*T2-.5*Q1*H1*Y(1)↑2*G(5,1)*L1/U1
560 T9=Q1↑2*T3
570 REM SC*,CC*,AC* FØR ELEMENT A
580 S1=T1+T2*C(1,1)+T3*C(1,1)↑2
590 C1=T4+T5*C(1,1)+T6*C(1,1)↑2
600 G1=T7+T8*C(1,1)+T9*C(1,1)↑2
610 REM CØEFFICIENTS FØR ELEMENT C
620 T1=-Y(3)↑4*(G(1,3)*L3↑3+G(3,3)*L3↑2*V3+G(6,3)*L3*V3↑2)/U1↑2
630 T2=Y(3)↑4*(G(2,3)*L3↑2+G(5,3)*L3*V3)/U1↑2
640 T3=-Y(3)↑4*G(4,3)*L3/U1↑2
650 T4=H1*Y(3)↑2*(G(7,3)*L3*V3+G(8,3)*L3↑2)+Q3*U1*T1
660 T5=-.25*H1*Y(3)↑2*G(5,3)*L3+Q3*U1*T2
670 T6=Q3*U1*T3
680 T7=Q3↑2*T1+2*Q3*H1*Y(3)↑2*(G(7,3)*L3*V3+G(8,3)*L3↑2)/U1
690 T7=T7-H1↑2*P(3)/2+G1+G2-A5
700 T8=Q3↑2*T2-.5*Q3*H1*Y(3)↑2*G(5,3)*L3/U1
710 T9=Q3↑2*T3
720 REM SØLUTIØN ØF CURVATURE FØR ELEMENT C
730 IF 4*T9*T7<T8↑2 THEN 760
740 PRINT "ERRØR: 4AC>B↑2; STEP 4"
750 GØTØ 1530
760 X1=(-T8+SQR(T8↑2-4*T9*T7))/2/T9
770 X2=T7/T9/X1
780 PRINT
790 PRINT "THE VALUES ØF C(3,1) ARE:"X1;X2
800 PRINT "PICK LARGE ØR SMALL";
810 INPUT X$
820 C(3,1)=X1
830 IF ABS(X1)>ABS(X2) THEN 850
840 C(3,1)=X2
850 IF X$(:1,1)="L" THEN 920
860 C(3,1)=X1
870 IF ABS(X1)<ABS(X2) THEN 890
880 C(3,1)=X2
890 T7=T7-G1-G2+A5
900 C(3,2)=C(3,1)-L3
910 REM SC*,CC*,AC* FØR ELEMENT C
920 S3=T1+T2*C(3,1)+T3*C(3,1)↑2
930 C3=T4+T5*C(3,1)+T6*C(3,1)↑2
940 G3=T7+T8*C(3,1)+T9*C(3,1)↑2
950 REM CØEFFICIENTS FØR ELEMENT B
960 T1=-Y(2)↑4*(G(1,2)*L2↑3+G(3,2)*L2↑2*V2+G(6,2)*L2*V2↑2)/U1↑2
970 T2=Y(2)↑4*(G(2,2)*L2↑2+G(5,2)*L2*V2)/U1↑2
980 T3=-Y(2)↑4*G(4,2)*L2/U1↑2
990 T4=H1*Y(2)↑2*(G(7,2)*L2*V2+G(8,2)*L2↑2)
1000 T5=-.25*H1*Y(2)↑2*G(5,2)*L2
1010 REM SØLUTIØN ØF CURVATURE FØR ELEMENT B
1020 C(2,1)=(A6-C1-C3-T4)/T5
1030 C(2,2)=C(2,1)-L2
1040 C2=T4+T5*C(2,1)
1050 S2=T1+T2*C(2,1)+T3*C(2,1)↑2
>
```

```
1060 REM COMPUTATION OF LA'
1070 L(I1)=S1+S2+S3
1080 PRINT "C(1)","C(3)","LA'"
1090 PRINT C(1,1),C(3,1),L(I1)
1100 REM NEXT LINE IS EXIT
1110 IF ABS(L(I1)-A7)<1E-3 THEN 1530
1120 C(1,1)=C(1,1)+.0001
1130 NEXT I1
1140 C(1,1)=C(1,1)-.0004
1150 REM SOLUTION FOR PARABOLIC COEFFICIENTS
1160 FOR I1=1 TO 3
1170 A(I1,1)=(C(1,1)+I1*.0001)↑2
1180 A(I1,2)=C(1,1)+I1*.0001
1190 A(I1,3)=1
1200 A(I1,4)=L(I1)
1210 NEXT I1
1220 A(1,2)=A(1,2)/A(1,1)
1230 A(1,3)=A(1,3)/A(1,1)
1240 A(1,4)=A(1,4)/A(1,1)
1250 A(2,2)= A(2,2)-A(2,1)*A(1,2)
1260 A(3,2)=A(3,2)-A(3,1)*A(1,2)
1270 A(2,3)=(A(2,3)-A(2,1)*A(1,3))/A(2,2)
1280 A(2,4)=(A(2,4)-A(2,1)*A(1,4))/A(2,2)
1290 A(3,3)=A(3,3)-A(3,1)*A(1,3)-A(3,2)*A(2,3)
1300 A(3,4)=(A(3,4)-A(3,1)*A(1,4)-A(3,2)*A(2,4))/A(3,3)
1310 T3=A(3,4)
1320 T2=A(2,4)-A(2,3)*T3
1330 T1=A(1,4)-A(1,2)*T2-A(1,3)*T3
1340 T3=T3-A7
1350 IF 4*T1*T3<T2↑2 THEN 1390
1360 PRINT "ERROR: 4AC>B↑2; STEP 8"
1370 GOTO 1530
1380 REM SOLUTION OF NEW VALUE OF CURVATURE FOR ELEMENT A
1390 X1=(-T2+SQR(T2↑2-4*T1*T3))/2/T1
1400 X2=T3/T1/X1
1410 PRINT
1420 PRINT "THE FIRST CURVE FOR THE NEXT TRIAL CAN BE "X1" OR "X2
1430 PRINT "PICK LARGE OR SMALL";
1440 INPUT X$
1450 C(1,1)=X1
1460 IF ABS(X1)>ABS(X2) THEN 1480
1470 C(1,1)=X2
1480 IF X$(:1,1)="L" THEN 430
1490 C(1,1)=X1
1500 IF ABS(X1)<ABS(X2) THEN 430
1510 C(1,1)=X2
1520 GOTO 430
1530 REM EXIT: DATA SUMMARY OUTPUT PRINTED
1540 FOR I1=1 TO 10
1550 PRINT
1560 NEXT I1
1570 PRINT "VARIABLE",,"ELEMENT"
1580 PRINT ,1,2,3
1590 PRINT "POWER",P(1),P(2),P(3)
1600 PRINT "CURVATURE",L1,L2,L3
>
```

```
1610 PRINT "CURVE 1",C(1,1),C(2,1),C(3,1)
1620 PRINT "CURVE 2",C(1,2),C(2,2),C(3,2)
1630 PRINT "AØR",Y(1),Y(2),Y(3)
1640 PRINT "SPACING","           "S(1)"        "S(2)
1650 PRINT "GLASS",Z(1),Z(2),Z(3)
1660 PRINT "INDEX",N(1),N(2),N(3)
1670 PRINT "V#",V(1),V(2),V(3)
1680 PRINT "FØCAL LENGTH="F1
1690 PRINT "MAXIMUM APERTURE="F2
1700 PRINT "MAXIMUM FIELD ANGLE="F3
1710 FØR I1=1 TØ 10
1720 PRINT
1730 NEXT I1
1740 END
>
```

APPENDIX 2

List of Variables

Variable	Program Used In	Description
A1	1	Aim Petzval Curvature
A2	1	Aim Longitudinal Chromatic
A3	1	Aim Lateral Chromatic
A4	1	Computed Lateral Chromatic
A5	Both	Aim Astigmatism=Asts'
A6	Both	Aim Coma=Comas'
A7	Both	Aim Spherical=LA'
A(x,y)	Both	Array members for Crout method
Cx	2	Coma contribution for element x
C(x,y)	2	Curvature of surface y, element x
		For Newton-Raphson method:
D1	1	ΔK for run with $\Delta y_b=0$
D2	1	ΔT'ch for run with $\Delta y_b=0$
D3	1	Δy_b for run with $\Delta y_c=0$
D4	1	Δy_c for run with $\Delta y_b=0$
D5	1	D5=D3 from previous run iteration
D6	1	D6=D4 from previous run iteration
F1	Both	Focal length
F2	Both	Maximum F/number
F3	Both	Maximum field angle
Gx	2	Astigmatism contribution for element x
G(x)	1	Glass name for element x
G(x,y)	2	G-sum number x for element y
H1	Both	Image plane intersect height for paraxial principal ray
I1	Both	Loop variable
K1	Both	Aim Space Ratio, K

Variable	Program Used In	Description
K2	1	Computed space ratio
Lx	2	Total curvature, c, for element x
L(x)	2	LA' for run through x
M1	Both	Reference name, called "Lens Designation" in computer output
N1	1	Counter to keep track of the part of the Newton-Raphson procedure being executed
N1	2	Check to verify that correct data file was being accessed
N(x)	Both	D index of refraction for element x
P(x)	Both	Power of element x
Qx	Both	Q constant for element x
S1	1	$\partial K/\partial y$
S2	1	$\partial K/\partial y$
S3	1	$\partial T'ch/\partial y$
S4	1	$\partial T'ch/\partial y$
Sx	2	Spherical contribution for element x
S(x)	Both	Spacing between element x and element x+1
Tx	Both	Variable for temporary storage, also for aberration coefficients
U1	Both	u_0' also written as u_k'
U2	1	Angle for incoming paraxial principal ray
U3	1	Angle for incoming marginal ray
U4	1	Angle for marginal ray entering element 2
U5	1	Angle for marginal ray entering element 3

Variable	Program Used In	Description
U(x)	1	Variable used to store only the Y(x) values needed in the second program
Vx	Both	The v constant for element x
V(x)	Both	V number for glass of element x
Xx	2	Variable for temporary storage
X$	2	String variable for choice of "LARGE OR SMALL?"
Y(x)	Both	For x=1 to 3, ray height for marginal ray at element X. For x=4 or 5, ray height of paraxial principal ray at element 1 or 3, respectively
Z(x)	2	Glass name for element x

APPENDIX 3

Example of Input/Output

Using the example from Dr. Kingslake's notes:

```
WHAT IS LENS DESIGNATIØN  ?KTEST
WHAT IS THE DESIRED FØCAL LENGTH  ?10
WHAT IS THE DESIRED MAXIMUM APERTURE  ?4.5
WHAT IS THE DESIRED MAXIMUM FIELD ANGLE (DEG)    ?20
GLASS FØR ELEMENT 1   ?SK16
N( 1)=  ?1.6203
V( 1)=  ?60.3
GLASS FØR ELEMENT 2   ?F4
N( 2)=  ?1.6164
V( 2)=  ?36.6
GLASS FØR ELEMENT 3   ?SK16
N( 3)=  ?1.6203
V( 3)=  ?60.3
WHAT IS THE AIM VALUE FØR:
PETZVAL CURVATURE   ?.035
L'CH      ?-.02
T'CH      ?0
AST'S     ?-.09
CØMA      ?.0025
LA'       ?-.08
K         ?1
```

Y(2)		Y(3)	T'CH
.883889	2.41458	1.00000	-1.13694E-02
.866339	1.45233	.954036	-2.13682E-03
.863186	1.22181	.954990	-7.60330E-04
.861771	1.12788	.955945	-2.52056E-04
.861411	1.09416	.956901	-1.21136E-04
.861342	1.07541	.957858	-8.37574E-05
.861323	1.05923	.958816	-6.24511E-05
.861313	1.04354	.959775	-4.43484E-05
.861306	1.02806	.960735	-2.77336E-05
.861301	1.01276	.961695	-1.23333E-05
.861299	1.00003	.962503	-1.31969E-07
.861298	1.00000	.962502	-9.64475E-12

```
PØWERS          .168101       -.304712        194056
SPACINGS               1.33748         1.33748
```

```
WHAT IS DESIGNATIØN ØF LENS   ?KTEST

THE VALUES ØF C(3,1) ARE:-.674664     7.23061E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .270900           7.23061E-02   2.61735E-02

THE VALUES ØF C(3,1) ARE:-.674789     7.24315E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .271000           7.24315E-02   2.63005E-02

THE VALUES ØF C(3,1) ARE:-.674914     7.25568E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .271100           7.25568E-02   2.64270E-02

THE FIRST CURVE FØR THE NEXT TRIAL CAN BE  .227703 ØR  .360523
PICK LARGE ØR SMALL   ?S

THE VALUES ØF C(3,1) ARE:-.612252     9.89460E-03
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .227603           9.89460E-03  -9.83489E-02

THE VALUES ØF C(3,1) ARE:-.612419     1.00612E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .227703           1.00612E-02  -9.78416E-02

THE VALUES ØF C(3,1) ARE:-.612585     1.02276E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .227803           1.02276E-02  -9.73357E-02

THE FIRST CURVE FØR THE NEXT TRIAL CAN BE  .231417 ØR  .296016
PICK LARGE ØR SMALL   ?S

THE VALUES ØF C(3,1) ARE:-.618355     1.59972E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .231317           1.59972E-02  -8.04264E-02

THE VALUES ØF C(3,1) ARE:-.618517     1.61592E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .231417           1.61592E-02  -7.99689E-02

THE VALUES ØF C(3,1) ARE:-.618679     1.63211E-02
PICK LARGE ØR SMALL   ?S
C(1)              C(3)              LA'
 .231517           1.63211E-02  -7.95127E-02
```

```
THE FIRST CURVE FØR THE NEXT TRIAL CAN BE  .231410 ØR  .303055
PICK LARGE ØR SMALL   ?S

THE VALUES ØF C(3,1) ARE:-.618344     1.59862E-02
PICK LARGE ØR SMALL   ?S
C(1)           C(3)           LA'
 .231310        1.59862E-02  -8.04576E-02

THE VALUES ØF C(3,1) ARE:-.618506     1.61482E-02
PICK LARGE ØR SMALL   ?S
C(1)           C(3)           LA'
 .231410        1.61482E-02  -8.00000E-02
```

```
VARIABLE                        ELEMENT
              1                 2                 3
PØWER         .163101          -.304712          .194056
CURVATURE     .271000          -.494341          .312842
CURVE 1       .231410          -.263741          1.61482E-02
CURVE 2      -3.95900E-02       .230599          .296694
AØR           1.11111           .861298          .962502
SPACING                1.33748          1.33748
GLASS         SK16             F4                SK16
INDEX         1.62030           1.61640          1.62030
V#            60.3000           36.6000          60.3000
FØCAL LENGTH= 10
MAXIMUM APERTURE= 4.50000
MAXIMUM FIELD ANGLE= 20
```

APPENDIX 4

Aberration Equations

Equations for Elements 1 and 3:

For spherical aberration:

$$SC^* = \frac{-y^4}{u_k'^2}\left(G_1c^3 - G_2c^2c_1 + G_3c^2v + G_4cc_1^2 - G_5cc_1v + G_6cv^2\right)$$

can be placed in the form: $SC^* = a_0 + a_1c_1 + a_2c_1^2$

Where:

$$a_0 = \frac{-y^4}{u_k'}\left(G_1c^3 + G_3c^2v + G_6cv^2\right)$$

$$a_1 = \frac{+y^4}{u_k'^2}\left(+G_2c^2 + G_5cv\right)$$

$$a_2 = \frac{-y^4}{u_k'^2}G_4c$$

For coma contribution:

$$CC^* = -hy^2\left(0.25G_5cc_1 - G_7cv - G_8c^2\right) + Qu_k'\left(a_0 + a_1c_1 + a_2c_1^2\right)$$

can be placed in the form: $CC^* = a_3 + a_4c_1 + a_5c_1^2$

Where:

$$a_3 = +hy^2\left(+G_7cv + G_8c\right) + Qu_k'a_0$$

$$a_4 = -hy^2\left(0.25Gc\right) + Qu_k'a_1$$

$$a_5 = Qu_k'a_2$$

For astigmatism contribution:

$$AC^* = \frac{-h^2\varnothing}{2} + \frac{2Q\,hy^2}{u_k'^2}\left(-0.25G_5cc_1 + G_7cv + G_8c^2\right) + Q^2\left(a_0 + c_1a_1 + a_2c_1^2\right)$$

can be placed in the form: $AC^* = a_6 + a_7c_1 + a_8c_1^2$

Where:

$$a_6 = \frac{-h\varnothing}{2} + \frac{2Q\,hy^2}{u_k'}\left(G_7cv + G_8c^2\right) + Q^2a_0$$

$$a_7 = \frac{-0.5Q\,hy^2G_5c}{u_k'} + Q^2a_1$$

$$a_8 = Q^2a_2$$

Constants:

$$c = \varnothing/(N-1)$$

$$v = u/y$$

$$Q = \overline{y}/y$$

Equations for Element 2:

For spherical aberration:

$$SC = \frac{-y^4}{u'_k}(G_1 c^3 - G_2 c^2 c_1 + G_3 c^2 v + G_4 c c_1^2 - G_5 c c_1 v + G_6 c v^2)$$

can be placed in the form: $SC = b_0 + b_1 c_1 + b_2 c_1^2$

Where:

$$b_0 = \frac{-y^4}{u'_k}(G_1 c^3 + G_3 c^2 v + G_6 c v^2)$$

$$b = \frac{+y^4}{u'_k}(+G_2 c^2 + G_5 c v)$$

$$b = \frac{-y^4}{u'_k} G_4 c$$

For coma contribution:

$$CC = -hy^2(0.25 G_5 c c_1 - G_7 c v - G_8 c^2)$$

can be placed in the form: $CC = b_3 + b_4 c_1$

Where:

$$b_3 = +hy^2(+G_7 c v + G_8 c^2)$$

$$b_4 = -0.25 h y^2 G_5 c$$

For astigmatism contribution:

$$AC = \frac{-h\emptyset}{2} = b_5$$

can be placed in the form: $AC = b_5$

Equations for G-sums:

$$G_1 = N^2(N-1)/2$$

$$G_2 = (2N+1)(N-1)/2$$

$$G_3 = (3N+1)(N-1)/2$$

$$G_4 = (N+2)(N-1)/2N$$

$$G_5 = 2(N+1)(N-1)/N$$

$$G_6 = (3N+2)(N-1)/2N$$

$$G_7 = (2N+1)(N-1)/2N$$

$$G_8 = N(N-1)/2$$

APPENDIX 5

The Crout Method

Crout Method:

Given three simultaneous equations:

$$ax + by + cz = d$$

$$ex + fy + gz = h$$

$$ix + jy + kz = m$$

Where x, y and z are unknowns, the rest are constants

Set up "A matrix": $\begin{bmatrix} a & b & c & d \\ e & f & g & h \\ i & j & k & l \end{bmatrix}$

Then member A(2,3)=g, for example

Then:
```
A(1,1)' = A(1,1)
A(2,1)' = A(2,1)
A(3,1)' = A(3,1)
A(1,2)' = A(1,2)/A(1,1)
A(1,3)' = A(1,3)/A(1,1)
A(1,4)' = A(1,4)/A(1,1)
A(2,2)' = A(2,2) - A(2,1)'A(1,2)'
A(3,2)' = A(3,2) - A(3,1)'A(1,2)'
A(2,3)' = A(2,3) - A(2,1)'A(1,3)' / A(2,2)'
A(2,4)' = A(2,4) - A(2,1)'A(1,4)' / A(2,2)'
A(3,3)' = A(3,3) - A(3,1)'A(1,3)' - A(3,2)'A(2,3)'
A(3,4)' = A(3,4) - A(3,1)'A(1,4)' - A(3,2)'A(2,4)' / A(3,3)'
```

Finally:

```
z = A(3,4)'

y = A(2,4)' - A(2,3)'z

x = A(1,4)' - A(1,2)'y - A(1,3)z
```

APPENDIX 6

References

References:

John F. Carson, Thesis Advisor, Personal Correspondence

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"Comment on Design of Triplet Anastigmat Lenses of the Taylor Type," Smith, JOSA, v.40, pp.406-407 (1950)

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APPENDIX 7

Resources

Computer:

Xerox model Sigma Six, property of Rochester Institute of Technology.

Computer was accessed on line through teletype, using CP-V BASIC Language.

Access to the computer is open to any registered R.I.T. students.

Grant:

This thesis was aided by a grant from the Central Intelligence Agency of the United States Government.